Stagnation Enthalpy as Rocket Currency: A Comparative Efficiency Map Across Propulsion Families

Douglas C. Youvan

doug@youvan.com

www.youvan.ai

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Rockets don't "run on heat" in the everyday sense—they trade stagnation enthalpy for jet kinetic energy. That simple ledger explains why engines tuned far from stoichiometric often outperform their "maximum heat" counterparts: the right mixture and expansion turn more of the flow's total enthalpy into exhaust velocity. This paper proposes a compact, apples-to-apples metric for that conversion, $\eta_{stag\to jet} \coloneqq (I_{sp}\cdot g_0)^2 / (2\cdot c_p\cdot T_0)$, interpreting it as the fraction of chamber (stagnation) enthalpy realized as directed kinetic energy at the nozzle exit. Using representative I_{sp}, c_p, and T_0 for canonical engines—LOX/LH_2 (RS-25), methalox (Raptor-Vac), kerolox (Merlin-Vac), hypergols (LM Ascent), solids (vacuum SRM), ethanol/LOX (V-2), and hydrazine monoprop—we sketch a comparative "efficiency map" of how different propellant chemistries, pressures, mixture ratios, and nozzle strategies spend their h_0 budget. The result is a clear, one-number intuition: hydrogen engines sit at the top due to light exhaust; methalox and kerolox occupy the middle; hypergols and legacy kerolox trend lower; solids cluster near half; and monoprops appear deceptively "efficient" because their h_0 pool is small. We close with design implications: why fuel-rich operation wins, how γ and $\bar{M}$ shape exhaust velocity, and where future gains likely lie (mixture tailoring, higher area ratios in vacuum, and full-flow cycles that protect high h_0 while minimizing losses).

Keywords: stagnation enthalpy, specific impulse, exhaust velocity, exergy, mixture ratio, hydrogen engines, methalox, kerolox, hypergolic, solid rockets, nozzle expansion, molecular weight, dissociation, Brayton/rocket cycle, LM ascent engine.

Note: A collaboration with GPT-5. CC4.0. The author believes the LM engine oxidizer data is falsified.

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References

1) Motivation: Why “Heat” Isn’t the Right Objective

1.1 From \Delta G/\Delta H intuition to flow exergy in open systems

Chemistry gives an intuitive ladder: higher heat of reaction (\Delta H) and more negative Gibbs free energy (\Delta G) mean “more energy available.” That logic is correct for *closed* systems at fixed T, p, where \Delta G bounds the maximum non-PV work. A rocket, however, is an *open*, flowing, strongly nonisothermal device. It raises pressure and temperature in a combustor, then performs large PV work by expanding to a very low exit pressure. The useful output is not “heat absorbed by hardware,” but **directed kinetic energy of the exhaust** that yields thrust.

The open-system bookkeeping is **flow exergy** (availability). For a steady, adiabatic, single-stream device with no shaft work, the ideal specific work is

w_max = (h0_in − h0_out) − T_amb (s0_in − s0_out),

where h0 and s0 are **stagnation** (total) enthalpy and entropy, and T_amb is the environment temperature. A near-isentropic nozzle makes s0_out ≈ s0_in, so the penalty term is small; the useful work collapses to the **drop in stagnation enthalpy**. In other words, chemical exergy first becomes high h0 in the chamber, then the nozzle cashes that h0 out as jet kinetic energy.

Why not optimize \Delta H directly (e.g., by running at stoichiometric)? Because the mapping from chemical energy to jet speed depends on *composition* during expansion. The key lever in exhaust velocity is not “heat alone,” but the ratio of temperature to average molecular weight and the effective heat-capacity ratio:

V_e \propto sqrt((T0 / M_bar) * f(gamma, p_e/p_c)).

Fuel-rich operation often **lowers M_bar** (more H2, CO, N2) and moderates dissociation, so more of the available exergy emerges as momentum, even if the chamber temperature T0 is a bit lower than at stoich. Thus, maximizing \Delta H per unit fuel is *not* the same as maximizing exhaust velocity or I_sp.

1.2 Stagnation enthalpy as the conserved coin in nozzles

Define **stagnation enthalpy** h0 = h + V^2/2. In a well-mixed combustor, the bulk velocity is small, so h0 ≈ h_c (hot equilibrium products). Through a nozzle designed to be close to isentropic, **h0 is nearly conserved**, trading internal energy for directed kinetic energy at the exit:

V_e = sqrt[2 (h0_in − h0_out)] \approx sqrt[2 (h_c − h_e)].

For a calorically perfect stand-in, h0 = c_p T0 and one often writes the familiar perfect-gas form

V_e \approx sqrt{ (2 gamma / (gamma − 1)) * (R T0 / M_bar) * [1 − (p_e/p_c)^{(gamma − 1)/gamma}] }.

Three immediate implications follow:

1. **Composition matters as much as temperature.** Lower M_bar in the exhaust (via fuel-rich mixtures) boosts V_e and I_sp even if T0 is slightly lower. Chasing maximum T0 at stoichiometric composition pushes products toward heavier species (H2O, CO2, NOx) and deeper dissociation, which raises M_bar and saps nozzle effectiveness.
2. **Nozzle quality decides how much h0 becomes jet KE.** High area ratio (in vacuum), matched expansion (p_e near ambient), and low divergence/viscous losses keep the s0 penalty small and convert a larger fraction of h0 into V_e.
3. **Thermal limits and cooling ride along.** Running somewhat rich reduces flame temperature and material stress while preserving or improving V_e via composition. Designs that merely maximize temperature risk spending h0 on dissociation and wall heat load rather than on exhaust momentum.

Hence the slogan: **stagnation enthalpy is the rocket's currency; the mission is to spend it as exhaust velocity, not as wall heat or heavy molecules.** The right objective is to **maximize h0-to-jet conversion**, which means optimizing mixture ratio, chamber pressure, and nozzle expansion for low M_bar, favorable gamma, and minimal entropy production—not merely maximizing "heat."

2) A One-Number Metric

2.1 Definition: eta_stag->jet = (Isp*g0)^2 / (2*cp*T0)

Goal: quantify, with one scalar, how effectively an engine converts **chamber (stagnation) enthalpy** into **directed jet kinetic energy**.

- Define the conversion fraction
  eta_stag->jet := KE_per_kg_out / h0_in
  where KE_per_kg_out = (Isp*g0)^2 / 2 and h0_in ~ cp*T0.
- Final expression (dimensionless):
  eta_stag->jet = (Isp*g0)^2 / (2*cp*T0)

Interpretation:

- Numerator is the per-mass jet kinetic energy implied by the delivered Isp.
- Denominator is the available "enthalpy budget" per mass of exhaust at the chamber (total) state.

- The number is **not** a thermodynamic efficiency in the 1st-law sense (you still have nozzle losses, heat transfer, dissociation, etc.). It is an **h0-to-jet conversion index**: higher means more of the flow's total enthalpy appears as exhaust KE rather than as heavy products, entropy, or wall heat.

Use cases:

- Apples-to-apples comparison across propellant families and cycles.
- Sensitivity scans (mixture ratio, chamber pressure, area ratio).
- Design targeting (e.g., match O/F and nozzle to push eta upward for a given mission).

2.2 Assumptions and scope (equilibrium vs frozen, vacuum vs sea level)

Because eta_stag->jet is compact, you must be explicit about modeling choices:

(A) Chemistry model

- *Equilibrium (EQ):* composition adjusts continuously with local T,p. This tends to **lower M_bar** at high T0 (more dissociation), raising cp and changing gamma.
- *Frozen (FR):* composition fixed after the chamber; only thermodynamics change with expansion. FR often yields **higher KE fraction** than EQ for the same T0 because less re-equilibration soaks up enthalpy in the nozzle.
- Recommendation: report both if possible: eta_EQ and eta_FR, or state clearly which one underlies cp and T0.

(B) Reference point for Isp

- *Vacuum Isp:* best for comparing engines' conversion of h0 when nozzle is well expanded.
- *Sea-level Isp:* penalized by over/under-expansion and back-pressure; useful for liftoff stages but mixes nozzle matching into the metric.
- Recommendation: use **vacuum Isp** for the headline eta_stag->jet; optionally include sea-level in a table for completeness.

(C) Nozzle losses and thrust coefficient

- Our metric implicitly folds nozzle losses into Isp. If you want to separate "combustion quality" (c*) from "nozzle quality" (CF), you can compute an **ideal** eta using ideal Isp_ideal (EQ, matched expansion, isentropic nozzle) and then compare to **actual** eta from measured Isp.

(D) State definition

- T0, cp should be **chamber total** values (not wall film, not injector face). Use the modeled/estimated equilibrium chamber state at the chosen O/F and p_c.

(E) Scope limitations

- Multiphase flows (e.g., Al particles in solids) complicate cp and KE accounting; treat with care or note that eta is approximate.
- Very high area ratios and altitude start conditions approach ideal nozzle behavior; sea-level starts do not.

2.3 How to pick cp and T0 consistently across propellants

A defensible, repeatable recipe:

Step 1: Choose operating point

- Fix propellant pair, mixture ratio O/F (prefer the **performance-optimal O/F**, not stoich), chamber pressure p_c, and expansion regime (vacuum vs sea-level).
- State whether you assume EQ or FR through the nozzle.

Step 2: Compute chamber state

- Use a chemical-equilibrium solver (CEA-class) or a trusted table to obtain **T0 (chamber temperature)** and **composition** at (O/F, p_c).
- Record **gamma0 = cp0/cv0**, **M_bar0** (average molecular weight), and **cp0 = cp(T0, composition)**.
  Notes:
  - cp0 is **mixture cp** at T0. It is higher than cold-gas cp and rises with dissociation.
  - If you lack a solver, adopt literature ranges: e.g., kerolox T0 ~ 3500–3700 K, methalox ~ 3500–3650 K, hydrolox ~ 3400–3600 K at performance O/F; cp0 often 3–4 kJ/kg-K for hydrocarbon/methalox, somewhat lower for ethanol-rich legacy mixes, and varies with chemistry.

Step 3: Pick Isp consistent with the same assumptions

- For **ideal eta**: compute Isp_ideal from your nozzle model (isentropic, matched expansion) under the same EQ/FR assumption.

- For **as-flown eta**: use measured/spec Isp_vac (or Isp_sl) for that engine configuration.

Step 4: Compute and report

- Use **eta_stag->jet = (Isp*g0)^2 / (2*cp0*T0)** with g0 = 9.80665 m/s^2.
- Report three companions alongside eta to keep context:
  (i) O/F, p_c, expansion ratio;
  (ii) EQ vs FR;
  (iii) T0, cp0 (and optionally gamma0, M_bar0).

Step 5: Sensitivity checks

- Vary O/F by +/- 0.2 and re-compute (shows composition vs temperature tradeoffs).
- Shift p_c (affects dissociation and gamma slightly, and nozzle CF in practice).
- Toggle EQ vs FR to bracket real behavior.
- For solids or two-phase flows, provide a range (eta_min..eta_max) and note particulate KE if you model it separately.

Common pitfalls to avoid

- Mixing a **measured Isp** with a **theoretical (optimistic) T0, cp0** from a different O/F or p_c.
- Using **stoichiometric** T0 for a design that actually runs fuel-rich; this biases cp0,T0 high and underestimates eta.
- Omitting the EQ/FR declaration; eta can shift noticeably between these assumptions.

Done right, eta_stag->jet is a compact, transparent **h0-to-velocity spending score** that travels cleanly across propellants, cycles, and eras—useful for both back-of-envelope comparisons and design targeting.

3) Physics Primer: What Turns h0 into Velocity

3.1 Roles of T0, gamma, and M_bar in V_e

The nozzle's job is to convert **stagnation enthalpy** into **directed kinetic energy**. In the ideal-gas stand-in (good for intuition), the exit speed is

V_e ~= sqrt{ (2*gamma/(gamma-1)) * (R*T0/M_bar) * [1 - (p_e/p_c)^((gamma-1)/gamma)] }.

Key levers:

- **T0 (chamber total temperature):** Higher T0 raises the numerator inside the sqrt. But T0 does not act alone; composition changes with T0.
- **M_bar (average molecular weight of products):** Lower M_bar boosts V_e linearly inside the sqrt. This is often the *dominant* lever across propellant families (H2-containing exhausts are light; CO2/H2O-heavy exhausts are not).
- **gamma (cp/cv):** Larger gamma increases the expansion effectiveness factor 2*gamma/(gamma-1) and the pressure-ratio term. Gamma tends to fall as temperature rises and as the mix acquires more internal DOF (dissociation). Very high T0 can therefore *reduce* gamma, slightly blunting gains.
- **Expansion match:** The bracket term depends on p_e/p_c. Proper altitude/nozzle area ratio (A_e/A_t) aims for near-matched expansion (p_e ~= p_amb) to maximize the kinetic-energy take-off.

Rule of thumb: for a fixed nozzle and pressure ratio, **V_e tracks sqrt(T0/M_bar)** more than T0 alone. That is why chemistry and mixture ratio—which set M_bar and gamma via equilibrium—matter as much as raw heat release.

3.2 Why fuel-rich beats stoichiometric for Isp

"More heat" (maximize dH at stoich) does not guarantee "more V_e." The expansion sees the *products you made*, not the reactants you burned. Three coupled effects favor a fuel-rich optimum:

1. **Lower M_bar at rich mix:** Rich combustion shifts products toward light species (H2, CO, N2 remnants) and away from heavy H2O/CO2. Dropping M_bar raises V_e ~ sqrt(1/M_bar), often more than enough to offset a modest T0 decrease vs stoich.
2. **Dissociation penalty at stoich:** Very high T0 near stoichiometric drives strong dissociation (e.g., H2O -> H + OH). Energy bound up breaking bonds is not available as jet KE; some of it re-appears as internal energy that the nozzle cannot fully convert. Running slightly rich moderates dissociation, improving the "usable" fraction of h0.
3. **Materials and cooling:** Rich operation supplies extra fuel as a heat sink (film/regen cooling), enabling high chamber pressure and healthy CF without over-stressing hardware. Surviving longer at high p_c can be worth more Isp than chasing a few extra kelvin at stoich.

Net: The **Isp peak** for almost all practical pairs (LOX/LH2, LOX/CH4, LOX/RP-1, N2O4/Aerozine-50) sits **fuel-rich** of stoichiometric, precisely because **sqrt(T0/M_bar)** and gamma tilt the trade.

3.3 Gravity losses as time penalties, not chemistry limits

In vacuum (e.g., lunar operations), “gravity loss” is not a property of chemistry; it is a **time integral** you pay while thrust is not perfectly aligned to cancel weight:

Delta_v_required = Delta_v_mission + Delta_v_gravity + Delta_v_steering (drag ~ 0 on the Moon).

- **Gravity loss scales with burn time:** For a given mass ratio and Isp, higher thrust-to-weight (T/W) shortens the burn and reduces the integral of g over time. Throttleability (for precision) trades some gravity loss for control authority.
- **Chemistry matters only indirectly:** Better Isp can enable smaller propellant mass and/or higher T/W for the same structure, which *indirectly* trims gravity loss. But there is no “Gibbs shortcut” to beat gravity; you either finish the burn faster or shape the trajectory to reduce time fighting g.

Design takeaway: **maximize usable V_e** (via mixture and expansion) and **choose thrust levels and burn profiles** that minimize time spent paying the gravity tax. The propulsion optimum (fuel-rich for high V_e) and the guidance/controls optimum (adequate T/W, altitude-matched nozzles) together set the real delta-v you keep.

4) Comparative Survey by Propellant Family

4.1 LOX/LH2 (e.g., RS-25): high eta_stag->jet via low M_bar

Hydrogen engines win the h0-to-velocity game because the exhaust stays light even after equilibration. At performance O/F (~6), chamber T0 is high (~3400–3600 K), but the key lever is very low M_bar (water plus appreciable H2 at high T). Gamma is reasonably favorable; dissociation penalties are tempered by the prevalence of light species. With altitude-optimized area ratios and excellent nozzle efficiencies, vacuum Isp ~ 450 s maps to large (Isp*g0)^2, so eta_stag->jet is top-tier. Cycle choices (staged combustion, high p_c) preserve h0 and keep nozzle losses small. Tradeoffs: cryogenic complexity, large tanks, and tight turbomachinery margins.

Design cues: run fuel-rich, push p_c and expansion, protect hardware with robust regen; gains mostly come from higher area ratio and better altitude matching, not higher stoichiometric temperature.

4.2 LOX/CH4 (Raptor-Vac): mid-high with full-flow cycle and high p_c

Methane splits the difference between H2 and heavy hydrocarbons: higher density than LH2 but lighter exhaust than RP-1. At O/F ~3.4–3.7 and p_c in the 200–350 bar realm, T0 is ~3500–3650 K and M_bar is moderate; gamma is decent. Full-flow staged combustion keeps all hot streams fuel-rich, improving cooling and preventing localized stoich zones that would spike dissociation and wall heat. Vacuum Isp in the high-360s to ~380 s with big nozzles gives eta_stag->jet in the "mid-high" band.

Design cues: preserve h0 by minimizing entropy production in preburners, keep mixture slightly rich, and exploit very large expansion ratios in vacuum. Methalox especially rewards altitude-started upper stages.

4.3 LOX/RP-1 (Merlin-Vac): mid due to heavier exhaust and coking constraints

Kerosene's virtues are storability, density, and simplicity; the penalty is heavier exhaust (more CO2/H2O, higher M_bar) and soot/coking risks that constrain how rich you can run and how hot you can push hardware. Merlins operate fuel-rich (~2.5–2.7 O/F) to gain Isp and protect the chamber/nozzle, but composition limits keep eta_stag->jet in the middle of the pack (vac Isp ~ 345–350 s for vacuum variants). Chamber pressures are solid but below methalox full-flow regimes; nozzle expansion is very good on vac nozzles, yet sea-level engines must accept under/over-expansion losses.

Design cues: bias rich without hitting coking walls, raise p_c as materials allow, and harvest gains from higher A_e/A_t on upper stages; further improvements hinge on thermal housekeeping more than on chemistry.

4.4 Hypergols (LM Ascent): reliability vs conversion efficiency tradeoffs

N2O4/Aerozine-50 exemplifies operational reliability: storable, instant ignition, pressure-fed simplicity. But hypergolic exhaust has relatively high M_bar (N-bearing species, H2O/CO2) and lower gamma; to protect materials in pressure-fed chambers, T0 is not chased aggressively. Isp_vac ~ 310–320 s (classically) yields a mid-low eta_stag->jet compared with cryogenic families. What you gain is mission certainty, restart capability, and lower dry mass from simpler feed systems—mass fraction wins can offset raw conversion percent.

Design cues: choose mixture on the rich side for Isp and cooling, accept lower eta_stag->jet in exchange for reliability and dry-mass reductions; perfect for ascent/RCS where precision and readiness trump ultimate efficiency.

4.5 Solids (HTPB/Al): two-phase flow, chemistry limits, vacuum strengths

Modern composite propellants (HTPB binder + oxidizer + Al) run hot and dense, with high p_c potential and robust thrust. However, two-phase flow (Al/Al2O3 droplets and slag) complicates conversion: some h0 is parked in particulate internal/kinetic energy that the nozzle does not fully convert into directed jet KE. Exhaust M_bar is relatively high; gamma drifts down at high T due to added DOF and dissociation. Vacuum performance is competitive (Isp_vac often 280–300+ s for large boosters), and eta_stag->jet lands near the middle, sometimes a bit above, depending on how you count particulate KE.

Design cues: grain geometry sets thrust (hence gravity-loss profile); nozzle expansion in vacuum can be very effective; chemistry and two-phase penalties cap the conversion fraction more than hardware losses do.

4.6 Legacy kerolox (V-2 ethanol/LOX): temperature-limited designs

The A-4/V-2 ran diluted ethanol (with water) to keep T0 and wall heat flux survivable with 1940s materials and cooling. That choice lowered T0 and kept M_bar relatively heavy, pushing eta_stag->jet down compared to modern kerolox. Nozzle expansion and chamber pressure were modest by today's standards, so additional losses entered via CF and unideal expansion. The architecture was groundbreaking but tuned for *survivability* first, conversion efficiency second.

Design cues: with modern materials and better cooling, the same chemistry could run richer and hotter for higher eta—history documents why the original was held back.

4.7 Monoprop (hydrazine): high percent on small h0 pools

Decomposition thrusters (e.g., hydrazine over iridium catalyst) achieve Isp ~ 220–235 s at modest T0 compared with biprop rockets. Because cp*T0 (i.e., the h0 "pool") is comparatively small, even moderate Isp gives a **high eta_stag->jet** by the metric. That does **not** mean monoprops outperform biprops in absolute delta-v; it reflects that a larger fraction of their limited enthalpy becomes jet KE. They excel in simplicity, throttleability, and precise impulse bits, not in raw performance.

Design cues: keep catalyst beds healthy, manage thermal transients, and accept that the path to more delta-v is a different chemistry (biprop or electric), not squeezing much more eta from decomposition alone.

Cross-family takeaways

- The common pathway is identical: raise h0 in the chamber, convert it to V_e with minimal entropy and heavy-molecule penalties.
- Families rank primarily by achievable **M_bar** of exhaust at performance O/F and by how well **cycle/nozzle** preserve and spend h0.
- Pushing eta_stag->jet higher usually comes from (i) richer mixes that lighten products, (ii) higher, survivable p_c with good cooling, and (iii) larger, better-matched expansion in vacuum—far more than from chasing the largest stoichiometric T0.

5) Case Plots & Sensitivity

5.1 Mixture-ratio sweeps (eta vs O/F)

Purpose. Show where each propellant family actually *maximizes* h0-to-velocity conversion and why that point lies fuel-rich of stoichiometric.

How to plot.

- X-axis: O/F. Sweep across a practical band:
  • LOX/LH2: 4.5…7.0 (optimum ~5.5–6.2)
  • LOX/CH4: 3.0…4.2 (optimum ~3.4–3.8)
  • LOX/RP-1: 2.2…3.0 (optimum ~2.5–2.7)
  • N2O4/A-50: 1.3…2.1 (optimum ~1.5–1.7)
- For each O/F: compute chamber state (T0, cp0, gamma0, Mbar0) and Isp_vac, then eta_stag->jet = (Isp*g0)^2 / (2*cp0*T0).

What you will see.

- **Concave peak** fuel-rich of stoich: as O/F increases toward stoich, T0 rises but Mbar also rises and gamma falls due to heavier products and more dissociation; the peak eta occurs before stoich where sqrt(T0/Mbar) is best.
- **Hydrogen family**: broad, high plateau (eta less sensitive to small O/F shifts) because exhaust stays light (H2, H, OH) across a wide rich band.
- **Kerolox/methalox**: sharper peak; too-rich lowers T0 quickly, too-lean increases Mbar and dissociation penalty.
- **Hypergols**: lower crest and narrower optimum; nitrogen species and higher Mbar depress the peak.

Design takeaway. Choose O/F at or slightly richer than the eta peak to buy robustness against mixture-ratio dispersions and throttle-point shifts.

5.2 Chamber-pressure effects via gamma, dissociation, and CF

Purpose. Isolate how raising p_c (chamber pressure) changes both the chemistry and the nozzle's ability to spend h0.

Mechanisms.

- **Chemistry (equilibrium).** At higher p_c, for the same T0:
  • Equilibrium tends to **favor recombination** (less dissociation at given T), nudging gamma upward and Mbar upward.
  • Net effect on eta is mixed: slightly heavier products (bad) but a modest rise in gamma (good) and often slightly higher T0 due to better mixing/combustion completeness (good).
- **Nozzle/CF.** Higher p_c at fixed ambient increases the **pressure ratio** p_c/p_amb, boosting the ideal thrust coefficient CF if area ratio is adequate. Real nozzles also suffer proportionally smaller viscous/slot losses at higher Reynolds numbers. In practice, **Isp improves with p_c**, raising eta through the numerator.
- **Cooling/materials.** Higher p_c increases wall heat flux; designs usually push richer O/F and stronger cooling (regen, film) to maintain margins—choices that also help eta by keeping composition light.

How to plot.

- X-axis: p_c (e.g., 40…350 bar). For each p_c, recompute EQ chamber state and a matched-expansion Isp_vac (or a realistic CF if expansion is fixed). Plot two curves: EQ and frozen (FR) across the nozzle; FR typically yields a higher eta bound.

What you will see.

- **Monotone upward trend** in eta with p_c for modern cycles (staged/full-flow) until bounded by nozzle under-expansion or material limits.
- **Legacy designs** (low A_e/A_t): smaller gains; CF saturates early.

Design takeaway. Raising p_c helps primarily via **Isp_vac** (numerator). Chemistry changes are second-order but can be guided with slightly richer mixes at higher p_c to keep Mbar low and gamma acceptable.

5.3 Area-ratio and altitude (vacuum expansion benefits)

Purpose. Quantify how nozzle expansion "cashes out" h0. The same hot chamber can look mediocre at sea level and excellent in vacuum, purely by expansion match.

Mechanics reminder.

- For a given chamber state,
  V_e ~= sqrt{ (2*gamma/(gamma-1)) * (R*T0/Mbar) * [1 - (p_e/p_c)^((gamma-1)/gamma)] }.
  Driving **p_e/p_c** smaller (bigger area ratio, higher altitude) increases the bracketed term toward 1.
- **CF (thrust coefficient)** grows with pressure ratio and area ratio until **over-expansion** incurs separation at sea level. In vacuum, you can push A_e/A_t very high without separation risks.

How to plot.

- X-axis: area ratio A_e/A_t (e.g., 10…400). Make families of curves for several ambient pressures p_amb (sea level, 20 kPa, 1 kPa, vacuum). Compute Isp and eta at each point, holding O/F and p_c fixed.

What you will see.

- **Sea level:** eta increases with A_e/A_t up to the separation boundary, then drops (losses spike). Upper stages avoid this regime by not lighting at sea level.
- **High altitude / vacuum:** eta keeps climbing with A_e/A_t but with diminishing returns; once p_e ~ p_amb, further increases mainly trim residual pressure thrust losses.
- **Hydrogen engines** benefit disproportionately from large A_e/A_t because their low Mbar makes the ideal-gas expansion assumption closer to reality and nozzle viscous losses relatively smaller.

Design takeaway. If the mission allows altitude start, spend mass on **bigger vacuum nozzles**; the eta gains are clean and composition-agnostic. At sea level, prioritize **contoured nozzles and altitude-compensating concepts** (e.g., aerospikes, extendable bells) if you need high eta across a pressure range.

Putting the three sensitivities together

- **O/F** sets the chemical "quality" of h0 (T0, Mbar, gamma).

- **p_c** raises how well you can *use* it (higher CF, better mixing), nudging chemistry too.
- **A_e/A_t with altitude** decides how much of that quality actually becomes jet KE.

A practical sweep protocol for design trades:

1. Pick O/F on the **fuel-rich shoulder** of the eta peak.
2. Raise **p_c** until materials/cooling set the limit; re-tune O/F slightly rich as p_c rises.
3. Maximize **A_e/A_t** for the intended ignition altitude; keep sea-level starts in safe expansion.
4. Report **eta_EQ** and **eta_FR** to bracket reality, and accompany each eta with (O/F, p_c, A_e/A_t, Isp_vac, T0, cp0, gamma0, Mbar0) so the comparison is auditable, not a "single magic number."

6) Design Implications

6.1 Mixture tailoring for target missions (sea-level vs vacuum staging)

Sea-level starts (boosters).

- Objective: robust thrust and good Isp while avoiding separation and coking.
- Mix on the **rich shoulder** of the eta peak so that:
    1. Mbar stays low (lighter products),
    2. T0 is moderated for materials/cooling, and
    3. ignition/transient margins are generous.
- For kerolox, staying too rich risks soot/coke; for methalox, richer mix aids cooling and turbine life. Set O/F so that the **sea-level nozzle** (smaller Ae/At) is near matched expansion at max-q; accept a modest eta hit to keep plume-stability margins.

Vacuum starts (upper stages).

- Objective: maximize Isp by fully "cashing out" h0 in a large bell.
- Bias O/F **slightly richer** than the theoretical peak to lower Mbar and reduce dissociation; pair with **very high Ae/At**.

- With hydrogen, the eta plateau is broad; pick an O/F that tempers boiloff/cycle constraints while preserving Isp. With methalox, a mild rich shift often pays via lower Mbar and cooler walls, enabling higher pc or bigger bells.

Staging logic.

- Let **boosters** choose O/F for controllability and thermal headroom; let **uppers** choose O/F for maximum eta and Isp_vac. Cross-stage commonality is attractive operationally, but even small O/F deltas by stage can net real performance.

6.2 Cycle choices that preserve h0 (full-flow, rich preburners)

What "preserving h0" means.
Every leak of h0 to entropy or wall heat before the nozzle reduces the numerator of your performance fraction. Cycle architecture decides how much h0 you **protect** on the way to the main chamber.

- **Gas-generator (GG).** Simple and robust, but the GG exhaust is dumped or only partially recovered; some chemical exergy is spent off-line. Good Isp is still attainable, but eta is cycle-limited.
- **Staged combustion (SC).**
    - **Fuel-rich preburner (FR-SC):** keeps turbine flow reducing/cooler, limits oxidizer-side corrosion, and returns most h0 to the main chamber.
    - **Ox-rich preburner (OR-SC):** raises turbine specific work at lower mass flow; materials and oxygen compatibility are harder.
      Either way, SC **recycles** turbine work back into thrusting flow, preserving h0 compared with GG.
- **Full-flow staged combustion (FFSC).**
  Splits propellants into **both** rich and ox-rich preburners; all propellant passes turbines and rejoins in the main chamber. Benefits:

1. Lower turbine temperature per unit work (more mass flow through turbines),
2. Lower pump inlet pressures (cavitation margin),
3. Near-total **recovery of preburner h0** into the main expansion.

Net: FFSC best protects the h0 budget and supports higher pc, which boosts Isp and eta via CF.

Guideline. If you can afford the complexity, **move up the ladder** GG → SC → FFSC. Pair with fuel-rich operation in preburners to lighten products and protect hot parts; then tune main-chamber O/F on the rich shoulder.

6.3 Materials/cooling enabling higher T0 without excess dissociation

The trap: chasing higher T0 at stoich pushes dissociation and heavier equilibrium products in the nozzle, which can **lower** V_e despite higher heat release. The right move is **raising survivable T0 while keeping composition favorable** (low Mbar, decent gamma).

Cooling toolset.

- **Regenerative cooling:** high-effectiveness heat pickup into fuel; richer main O/F increases sink capacity and reduces wall heat flux.
- **Film/curtain cooling:** small, sacrificial fuel fractions along walls; manage mixing so film does not erode Isp.
- **Ablatives / liners:** provide transient protection for short burns or start transients; trade mass for simplicity.
- **Transpiration/porous walls (advanced):** superb heat transfer; complexity and mass are nontrivial.

Materials & structures.

- **Cu-based channel jackets** (high k) with high-strength overwraps for chambers;
- **Ni-superalloys** or **C/SiC composites** for throats and hot bells;
- **Coatings** to resist ox-rich chemistry and reduce catalytic recombination on walls (which otherwise dumps h0 into surface heat).
- Additive manufacturing enables **integrated cooling channels** and graded materials that push allowable heat flux higher without mass spikes.

Chemistry management.

- Running **slightly richer** both cools hardware and eases dissociation; it also biases products toward H2/CO.
- Choose **pc high** but within cooling capacity; higher pc improves CF and mixing, often raising Isp more than a small T0 increase would.

Design recipe.

1. Set O/F on the **rich shoulder** where d(eta)/d(O/F) is small (robust to dispersions).
2. Select the **highest pc** your cooling/materials support; re-tune O/F richer as pc rises.
3. Invest in **large Ae/At** where altitude permits; this is the cleanest way to turn h0 into V_e.
4. Use cycle architecture (prefer SC/FFSC) that **recycles preburner h0** and minimizes entropy production before the main nozzle.

Bottom line. You do not maximize Isp by maximizing T0 in isolation; you maximize it by **co-optimizing O/F, pc, and Ae/At** under a cycle and cooling stack that keeps **composition light, gamma reasonable, and entropy growth small**—i.e., by spending the **stagnation enthalpy** you already have on **velocity**, not on **walls and heavy molecules**.

7) Limits, Caveats, and How Not to Misuse the Metric

7.1 Data spread, cp(T) modeling, and real-gas departures

What varies. Chamber temperature T0, mixture cp(T0), gamma(T0), and even Isp depend on O/F, p_c, and whether you assume equilibrium (EQ) or frozen (FR) chemistry. Reported "typical" values in the literature can differ by 5–15%—enough to swing eta_stag->jet by a visible amount.

Implications for eta.

- Our metric uses: eta_stag->jet = (Isp*g0)^2 / (2*cp*T0). If cp*T0 is 10% high because you used a hot, stoich table for an engine that actually runs fuel-rich, your eta will be 10% low.
- cp is a **mixture** quantity at the chamber state. Using constant cp for a "generic hot gas" underestimates cp for dissociating mixtures and biases eta high.
- Real-gas effects: vibrational DOF, dissociation, and finite-rate chemistry alter cp(T), gamma(T), and the available h0. Ideal-gas stand-ins are OK for trends, not for tight numbers.

Good practice.

- State the tuple you used: (O/F, p_c, T0, cp0, gamma0, M_bar0, EQ/FR).
- Provide uncertainty bands (e.g., cp0 within +/- 0.2 kJ/kg-K; T0 within +/- 75 K).
- When comparing engines, **use a consistent modeling stack** (same solver, same assumptions) or explicitly bracket with low/high cases.

7.2 Equilibrium vs frozen chemistry through the nozzle

Why it matters.

- **EQ nozzle:** composition re-equilibrates as p,T fall. Some chamber enthalpy is "spent" on recombination/redistribution of species; gamma and M_bar evolve with x.
- **FR nozzle:** composition is fixed at the chamber "freeze point"; enthalpy mostly converts to kinetic energy without chemistry doing extra bookkeeping on the way out.

Effect on eta.

- For the same chamber state, **eta_FR >= eta_EQ** (often by a few to ~10 percentage points), because less enthalpy is diverted to chemical re-arrangement in the nozzle.
- Freeze point is itself design-dependent (residence time, mixing, p_c). Assuming "fully frozen at the throat" is generous; assuming "fully equilibrium to the exit" is conservative.

How not to misuse.

- Do **not** mix Isp from a test (which already bakes in some degree of freezing and real losses) with an idealized EQ cp*T0 from a different O/F. That hybrid can exaggerate eta.
- If you publish a single eta, say which you used: eta_EQ or eta_FR. Better: publish **both** to bracket reality, plus the measured eta_test using the reported Isp_vac.

7.3 When thrust coefficient and nozzle losses dominate the story

Where the denominator is not the issue.

- Our denominator (cp*T0) tracks available h0. But many practical shortfalls live in the **numerator** via Isp: separation, under-/over-expansion, non-ideal wall divergence, finite boundary layers, heat transfer, and off-design plume behavior. In these cases, **CF (thrust coefficient)** and nozzle losses dominate performance.

Sea-level traps.

- Over-expanded nozzles at liftoff: shock-induced separation, side loads, big Isp penalties. Your chemistry may be perfect; eta still falls because Isp drops.
- Altitude change during ascent: a fixed bell can only be matched at one ambient; everywhere else, you leave Isp on the table.

Two-phase and particulate flows.

- Solids with Al/Al2O3 carry portions of h0 in droplets/particles that do not fully convert to directed KE. Depending on how you count "useful KE," eta can look worse or better; be explicit about whether particulate KE is included.

Cycle and plumbing losses.

- Gas-generator cycles discard some exergy; staged/FFSC recover it. If you compare eta across cycles without noting this, you might blame "chemistry" for what is mostly **cycle architecture**.

How not to misuse.

- Do not rank engines by eta alone when the mission is sea-level ascent; **nozzle matching** and **CF** will swamp small differences in cp*T0 bookkeeping.
- When diagnosing a low eta, check the obvious first: expansion ratio vs altitude, separation margins, film-coolant ingestion, and divergence losses. Fixing those may raise Isp (and eta) far more than any mixture tweak.
- Always pair eta with the context line: (Isp_ref, altitude, Ae/At, p_c, O/F, EQ/FR). Without that, a single number invites false conclusions.

Rule of thumb.

- Use eta_stag->jet as a **design lens**, not a scoreboard trophy. It's excellent for seeing *where* your h0 is being "spent" (walls, heavy molecules, entropy) and for guiding trades (richer mix, higher Ae/At, better cycle). It is not a substitute for full nozzle/trajectory analysis, especially at changing ambient pressure.

8) Outlook

8.1 Where η_stag→jet can still grow (ultra-high expansion, altitude starts)

Two levers reliably raise the h_0→velocity spend without changing chemistry: **bigger expansion** and **starting high**.

- **Ultra-high area ratios ($A_e/A_t \gg 200$):** In vacuum, driving $p_e/p_c \to 0$ makes the pressure-ratio term in V_e approach its ideal limit, lifting Isp and η_stag→jet. Practical paths: extendable bells, deployable/rollable skirts, dual-bell and altitude-compensating contours (aerospike, plug, expansion-deflection) for off-design robustness.

- **Altitude starts:** Lighting upper stages above the sensible atmosphere eliminates separation limits and back-pressure loss. The same chamber h_o that looks "average" at sea level becomes "excellent" when you can run the big bell in matched expansion.
- **Cycle + altitude synergy:** Higher p_c from staged/full-flow cycles increases p_c/p_amb, compounding gains from high A_e/A_t once you're out of the soup.

8.2 Exotic propellants and afterburning expansion concepts

Chemistry tweaks can make the exhaust lighter or keep it "energetically alive" through the nozzle—both help η.

- **Light-exhaust blends:** Hydrogen remains king, but **methane-rich cocktails** (methalox biased rich) and **ammonia → cracked-ammonia** schemes aim to import H_2-like $\bar{M}$ without full cryo burden. Long-term, **metal hydrides** as in-situ H_2 sources are intriguing if mass-effective.
- **Dissociation-friendly mixes:** Species that partially dissociate in the chamber (raising cp) yet **recombine exothermically in the nozzle** can pay back some enthalpy as directed KE—an "afterburning expansion." True equilibrium recombination is hard to harness, but tailored kinetics, catalytic wall treatments (to **avoid** heat-dumping surface recombination), and nozzle residence-time control may shift the balance.
- **Oxy-rich additives vs materials:** Ox-rich streams can improve turbine work and raise p_c, indirectly boosting η via CF, but demand coatings/alloys that survive radical oxygen.
- **Two-phase rethinks:** For solids, reducing particulate drag (smaller Al droplets, tailored oxide morphology) or harvesting particle KE via flow conditioning could narrow the conversion gap.

8.3 Benchmarking future engines with a common h_o ledger

To make η_stag→jet a durable yardstick, standardize the bookkeeping:

- **Report the tuple**: (O/F, p_c, A_e/A_t, ignition altitude, Isp_vac/SL, model = EQ or FR, T_o, $c_p(T_o)$, $\gamma(T_o)$, $\bar{M}(T_o)$). Publish both **ideal** (model-based) and **as-tested** η using measured Isp.
- **Bracket with EQ/FR**: give η_EQ and η_FR to bound chemistry-through-nozzle uncertainty; add an uncertainty bar from c_p/T_o spreads.
- **Stage-aware comparisons:** score boosters at sea-level design points and uppers at vacuum points; mixing conditions obscures nozzle vs chemistry effects.

- **Trajectory context:** accompany η with thrust-to-weight and burn profile summaries; gravity-loss budgets explain why two engines with similar η can deliver different mission Δv.
- **Open tables:** maintain a living, peer-audited database of representative engines (legacy → cutting edge) computed with the same solver and assumptions. That turns η_stag→jet from a clever back-of-envelope into a **shared currency** for propulsion trades—clarifying where gains still exist: richer mixes that lighten products, higher p_c under better cooling, and ever larger, better-matched expansion in the vacuum where rockets actually earn their keep.

Appendix A: Worked examples (parameter sets and eta calculations)

Conventions (copy-safe math):
g0 = 9.80665 m/s^2.
eta_stag->jet = (Isp*g0)^2 / (2*cp*T0).
All cp are effective mixture cp at chamber T0 (J/kg-K). T0 are chamber total temperatures (K).
Values are representative, not unique.

A1) LOX/LH2 upper stage (RS-25-class, vacuum)
Assume: O/F = 5.9, p_c = 200 bar, A_e/A_t large, EQ chemistry.
T0 = 3550 K, cp = 3.8e3, Isp_vac = 452 s.
Isp*g0 = 452*9.80665 = 4433 m/s.
eta = 4433^2 / (2*3800*3550) = 1.965e7 / 2.698e7 = **0.73** (73%).

A2) LOX/CH4 full-flow (Raptor-Vac-class)
Assume: O/F = 3.6, p_c = 330 bar, large A_e/A_t, EQ.
T0 = 3600 K, cp = 3.8e3, Isp_vac = 380 s.
Isp*g0 = 3727 m/s.*
eta = 3.889e6? → (3727^2=1.389e7) / (2*3800*3600=2.736e7) = **0.51** (51%).

A3) LOX/RP-1 vacuum variant (Merlin-Vac-class)
Assume: O/F = 2.6, p_c = 100 bar, large bell, EQ.
T0 = 3600 K, cp = 4.0e3, Isp_vac = 348 s.
Isp*g0 = 3410 m/s.*
*eta = 1.163e7 / (2*4000*3600=2.88e7) = **0.40** (40%).

A4) N2O4/Aerozine-50 (LM Ascent-class)
Assume: O/F = 1.6, p_c = 10 bar (pressure-fed), EQ/FR bracket.
T0 = 3350–3450 K, cp = 3.1e3–3.5e3, Isp_vac = 311 s.
Isp*g0 = 3051 m/s.*
*Denominator range: 2*cp*T0 = 2.08e7…2.42e7.
eta = 9.31e6 / (2.08e7…2.42e7) = **0.39…0.45** (39–45%).

A5) V-2 kerolox (ethanol 75% + water 25%) legacy
Assume: O/F ~ 1.9–2.0 (effective), p_c ~ 15–20 bar, modest bell.
T0 = 2950–3050 K, cp = 2.2e3–2.6e3, Isp_vac ~ 240–245 s.
Isp*g0 = 2354–2401 m/s.*
*eta = (5.54e6…5.76e6) / (2*cp*T0 ~ 1.30e7…1.59e7) = **0.35…0.44** (35–44%).

A6) Hydrazine monoprop decomposition thruster
Assume: catalyst bed, T0 ~ 1150–1250 K, products (N2, H2, NH3), cp ~ 2.4e3–2.8e3, Isp_vac = 225–235 s.

Isp*g0 = 2207–2304 m/s.*
*eta = (4.87e6…5.31e6) / (2*cp*T0 ~ 5.52e6…7.00e6) =* ***0.70…0.96*** *(70–96%).*
Note: The high percent reflects a ***small h0 pool*** *(cp*T0) rather than superior absolute performance.

Checklist for reproducing each example: fix (O/F, p_c, A_e/A_t, EQ/FR) ⇒ compute chamber state (T0, cp) ⇒ pick Isp_vac consistent with nozzle/altitude ⇒ apply eta formula. Report the full tuple with uncertainties.

Appendix B: Mapping eta_stag->jet to classical performance (c*, CF, Isp)

Classical relations
Isp = (CF * c*) / g0.
c* ("c-star") depends on chamber state and chemistry:
c* = sqrt(R*T0/Mbar) * [(gamma)^(1/2) * ((2/(gamma+1))^((gamma+1)/(2*(gamma-1))))].
CF (thrust coefficient) captures nozzle expansion and losses: function of p_e/p_c, A_e/A_t, contour, viscous/divergence effects, separation, etc.

Rewrite eta in classical factors
eta_stag->jet = (Isp*g0)^2 / (2*cp*T0)*
*= (CF^2 * c*^2) / (2*cp*T0).

Implications

1. *Chemistry lever (c):** Higher T0 helps, but c* rises fastest when Mbar falls and gamma is favorable. This is why **fuel-rich** mixtures (lighter products) can increase c* even if T0 dips slightly.
2. **Nozzle lever (CF):** For a fixed chamber, matching expansion (p_e ~ p_amb), larger A_e/A_t, and low divergence losses raise CF, directly boosting eta via CF^2.
3. **Separation & off-design:** At sea level, over-expansion collapses CF; eta falls even if c* (chemistry) is unchanged.
4. **Cycle/exergy preservation:** Architectures that **recycle preburner work** (staged/FFSC) and minimize entropy before the throat effectively preserve the c* you paid to generate, and support higher p_c, which also raises achievable CF in practice.

Takeaway: Use eta as a compact "spend score," but diagnose improvements via **c*** (chemistry, O/F, T0, Mbar, gamma) and **CF** (nozzle/altitude). Gains compound: small c* improvement times a CF improvement squares into eta.

Appendix C: Quick-reference tables (representative engines & assumptions)

All values are illustrative, centered on commonly cited operating points. Provide brackets where spread is material.

C1) LOX/LH2 (RS-25-class upper stage)
O/F: 5.9 | p_c: 200 bar | A_e/A_t: 77–110 | Altitude: vacuum
Model: EQ
T0: 3500–3600 K | cp: 3.6–3.9 kJ/kg-K | gamma0: 1.21–1.25 | Mbar0: 9–13 g/mol
Isp_vac: 448–452 s
eta_stag->jet: **0.70–0.74**

C2) LOX/CH4 (Raptor-Vac-class)
O/F: 3.5–3.7 | p_c: 300–350 bar | A_e/A_t: 150–200 | Altitude: vacuum
Model: EQ (FFSC cycle)
T0: 3550–3650 K | cp: 3.6–3.9 kJ/kg-K | gamma0: 1.20–1.24 | Mbar0: 16–20 g/mol
Isp_vac: 370–380 s
eta_stag->jet: **0.49–0.54**

C3) LOX/RP-1 (Merlin-Vac-class)
O/F: 2.5–2.7 | p_c: 90–110 bar | A_e/A_t: 117 | Altitude: vacuum
Model: EQ
T0: 3500–3650 K | cp: 3.8–4.2 kJ/kg-K | gamma0: 1.18–1.22 | Mbar0: 20–24 g/mol
Isp_vac: 345–350 s
eta_stag->jet: **0.38–0.42**

C4) N2O4/Aerozine-50 (LM Ascent-class)
O/F: 1.5–1.7 | p_c: 9–12 bar | A_e/A_t: ~45 | Altitude: vacuum
Model: EQ/FR bracket
T0: 3300–3450 K | cp: 3.1–3.5 kJ/kg-K | gamma0: 1.18–1.21 | Mbar0: 22–26 g/mol
Isp_vac: 308–312 s
eta_stag->jet: **0.39–0.45**

C5) Solids (HTPB/Al, large vacuum motor)
O/F: fixed by grain | p_c: 60–100 bar | A_e/A_t: 40–80 | Altitude: vacuum
Model: multiphase (note: particulate KE, oxide droplets)
T0: 3200–3400 K | cp: 2.8–3.4 kJ/kg-K | gamma0: 1.16–1.20 | Mbar0: 24–30 g/mol
Isp_vac: 285–305 s
eta_stag->jet: **0.45–0.55** (definition depends on particulate KE accounting)

C6) V-2 kerolox (ethanol/water), legacy
O/F: ~1.9 | p_c: 15–20 bar | A_e/A_t: ~10–12 | Altitude: near-vac (upper flight)
Model: EQ
T0: 2950–3050 K | cp: 2.2–2.6 kJ/kg-K | gamma0: 1.20–1.24 | Mbar0: 22–26 g/mol
Isp_vac: 240–245 s
eta_stag->jet: **0.35–0.44**

C7) Hydrazine monoprop (CAT bed)
Chemistry: decomposition | p_c: 5–20 bar | A_e/A_t: 20–40 | Altitude: vacuum
Model: FR-lean (composition largely fixed post-bed)
T0: 1150–1250 K | cp: 2.4–2.8 kJ/kg-K | gamma0: 1.30–1.36 | Mbar0: 10–16 g/mol
Isp_vac: 225–235 s
eta_stag->jet: **0.70–0.95** (small cp*T0 pool; percent is high though absolute Isp is low)

Usage note: Always accompany eta with the full tuple (O/F, p_c, A_e/A_t, altitude, model, T0, cp0, gamma0, Mbar0, Isp_ref). If you change any of those, recompute eta; small shifts in cp(T0) or Isp can move eta by several points.

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Notes: Where a value (e.g., Isp, T_o) is mission- or configuration-dependent, we paired primary technical sources (NASA fact sheets, NTRS reports, manufacturer data) with standard texts (Sutton, Hill & Peterson) and used CEA references for chemistry assumptions.